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On rashleighite, a new mineral from Cornwall, intermediate between turquoise and chalcosiderite.

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[Read March 11, 1937.]

THE mineral here described was at first considered to be an iron-rich variety of turquoise and was described by myself as such when this paper was read before the Society in 1937. At that time only a partial analysis had been made; since then Dr. J. A. Smythe of King's College, Newcastle-upon-Tyne, has most kindly undertaken at my instigation careful analyses of the mineral from both of its localities, Bunny mine, St. Austell, and Castle-an-Dinas wolfram mine, St. Columb Major. As a result of these two analyses, which are in close agreement, it is evident that the mineral is a new one, intermediate between turquoise and the two minerals chalcosiderite and andrewsite, and forming a middle member of what is probably an isomorphous group. The name rashleighite commemorates Philip Rashleigh, F.R.S., F.G.S., F.S.A., 1729–1811, of Menabilly, Cornwall, one of the earliest of Cornish mineralogists and famous for having amassed the finest collection of Cornish minerals ever made.

The table of analyses given below shows the relationships of the various members of the group and their respective specific gravities. The crystal system to which these minerals belong has only been established in the case of turquoise and chalcosiderite which are triclinic. Henwoodite (Sp. gr. 2·67) would seem to belong to this group, but an examination of a series of specimens shows that it is apparently a mineral of variable composition and the sole analysis by J. H. Collins, for which he did not claim a high degree of accuracy, cannot be considered very satisfactory, and for this reason it has not been included in the table and indeed it does not fit in well.

	1.	2.	3.	4.	5.	6.	7.	8.
P_2O_5	32·86	33·72	—	31·59	28·60	33·82	29·93	26·09
As_2O_5	—	—	—	0·48	2·11	—	0·61	—
Al_2O_3	40·19	32·75	—	21·63	20·84	10·45	4·45	0·92
Fe_2O_3	—	4·28	5	20·09	21·29	34·26	42·81	44·64
FeO	2·21	0·71	—	0·32	—	—	—	7·11
CuO	5·27	7·54	—	7·72	7·87	6·82	8·15	10·86
CaO	—	—	—	—	—	0·87	—	0·09
MgO	—	—	—	0·12	—	—	—	MnO 0·60
SiO_2	—	2·24	—	0·16	2·25	—	—	0·49
H_2O	19·34	18·96	—	17·40(+) 0·40(−)	16·45	13·70	15·00	8·79
	99·87	100·20	—	99·91	99·41	99·92	100·95	99·59
Sp. gr.	2·75	2·697–2·764	—	3·0	3·02	3·0	3·108	3·475

1. Turquoise, Persia. A. H. Church, Chem. News, 1864, vol. 10, p. 290.

2. Turquoise, Los Cerillos, New Mexico. H. Jung, Chemie der Erde, 1932, vol. 7, p. 81. [M.A. **5**–279.]

3. Ferri-turquoise, Lynch, Virginia, U.S.A., C. H. Robinson, The Mineralogist, Portland, Oregon, 1942, vol. 10, p. 44. [M.A. **8**–270.]

4. Rashleighite, Castle-an-Dinas mine, St. Columb Major, Cornwall. Analyst, J. A. Smythe.

5. Rashleighite, Bunny mine, St. Austell, Cornwall. Analyst, J. A. Smythe.

6. Alumo-chalcosiderite Schneckenstein, Saxony. A. Jahn and E. Gruner, Mitt. Vogtländ. Gesell, Naturfor., 1933, vol. 1, no. 8, p. 19. [M.A. **5**–391.]

7. Chalcosiderite, Phoenix mine, Linkinhorne, Cornwall. N. S. Maskelyne, Journ. Chem. Soc. London, 1875, vol. 28 (ser. 2, vol. 13), p. 591. Analyst, W. Flight. Also uranium oxide trace.

8. Andrewsite West Phoenix mine, St. Cleer, Cornwall. N. S. Maskelyne. Ibid., p. 486. Analyst, W. Flight.

Optical data for both turquoise and rashleighite are unfortunately lacking owing to the unsuitability of the material available. The results of an X-ray study of turquoise and chalcosiderite have been recently given by A. R. Graham and L. G. Berry,[1] but as Dr. F. A. Bannister points out, although powder photographs of turquoise, rashleighite, and chalcosiderite are all similar in pattern, only the complete investigation of the crystal structures will reveal how they differ. Analysis 5 of rashleighite gives a formula $CuO.3\frac{1}{2}(Al,Fe)_2O_3.2P_2O_5.9H_2O$, with molecular ratios $Al_2O_3 : Fe_2O_3 = 0{\cdot}2044 : 0{\cdot}1333$. [Cf. M.A. **10**–336.]

Bunny tin and wolfram mine, St. Austell, Cornwall

(Six-inch Ordnance map, Cornwall, 41 SE., 1908.)

This mine is situated in the heart of the china-clay district, on the south-east side of Hensbarrow Beacon, $3\frac{1}{2}$ miles north of St. Austell, on

[1] A. R. Graham and L. G. Berry, Amer. Min., 1947, vol. 32, p. 201 (abstract); A. R. Graham, Univ. Toronto Studies, Geol. Ser., 1948, no. 52 (for 1947), p. 39. [M.A. **10**–336.]

the west side of the road from that town to Roche. The mine was undoubtedly worked for tin at an early period.[1] In 1838 it was working under the name of St. Austell Hills mine, and after a period of abandonment was reopened from 1864 to 1875 as Old Bonney and Shelton (Bonney being merely a misspelling for Bunny). It was again reopened for tin and wolfram as Bunny mine in 1901 and continued working, not very successfully, until 1907, since when it has remained abandoned.

There are several more or less parallel lodes, similar in character, traversing the kaolinized granite in a north-east direction and underlying north-west. At the time of the last working three of the lodes were actually being worked, the most important being that known as the Main or no. 1 lode, and it was from this, particularly at the 80-fathom level, that the specimens of rashleighite here described were obtained. The Main lode consists of a series of parallel mineralized veinlets, each enclosed in greisen, the thickness of the greisen depending on the width of the veinlet. The greisen passes abruptly into either soft kaolinized granite or a fairly hard silicified granite. The veinlets vary in width from a mere string to 20 inches, their filling consisting of quartz with china-clay (kaolin), cassiterite, wolframite, and in places a good deal of rashleighite, tourmaline, gilbertite, and more rarely a little chalcosine, mispickel, and pyrite. A little purple fluorite occasionally coats joints on the adjoining kaolinized granite, while the greisen contains an abundance of topaz as a micro-constituent. While the mine was being worked between 1864 and 1875 the late Mr. J. H. Collins collected specimens of the rashleighite, but assumed the mineral to be chrysocolla, which in some specimens it certainly somewhat resembles, and in his pamphlet 'The Hensbarrow granite district' (Truro, 1878, p. 45) he says 'at Bunny some of the tin ores are coated with a beautiful green silicate of copper'. These specimens of rashleighite collected by Mr. Collins are now in my collection. Since that date a good deal of the mineral was collected by the late Mr. W. Boxhall of Treverbyn, Mr. F. H. Butler, and Mr. G. H.

[1] The name Bunny was used by the early Cornish miners to signify a kind of stockwork or ramification of veinlets of ore. W. Pryce, Mineralogia Cornubiensis, 1778, p. 317, defines it as 'A pipe of Ore. A great collection of Ore without any vein coming into or going from it'; either tin or copper ore. John Hawkins, On the stratified deposits of tin-stone, called tin-floors, &c. (Trans. Roy. Geol. Soc. Cornwall, 1822, vol. 2, p. 33), describes such a deposit at Botallack mine, St. Just, which was known as Grylls's bunny. At Bunny mine there are two large rudely circular pits adjoining one another, the site of ancient workings on a ramification of tin veinlets in the kaolinized granite and not to be confused with the numerous china-clay pits in their immediate neighbourhood. The comparatively modern underground mine workings are situated on the ground between these two pits.

Richards, the two latter being mineral dealers in London, and sold to collectors as chrysocolla. During 1905–1907 when the mine was last worked I went underground on several occasions and collected specimens from the 80-fathom level and from a qualitative examination assumed the mineral was turquoise. In 1931 Mr. Herbert J. Thomas of Truro made a partial quantitative analysis on material which he had collected that year on the old dumps and on the strength of this analysis in which the alumina and iron were not determined separately, he also assumed the mineral to be turquoise and a brief notice of the presentation by him of a specimen to the British Museum appeared in 'The Times' newspaper of November 30, 1931, the locality being given as St. Austell, Cornwall.

In colour the Bunny mine rashleighite is for the most part light blue-green, R. Ridgway's lichen-green, glaucous-green, and deep glaucous-green exactly matching the varying tints, while more rarely it is true turquoise-blue. The mineral, which occurs in some quantity, both fills the interstices and encrusts roughly crystallized prisms of greyish quartz, which projecting from a groundmass of quartz on the greisen walls form the central part of the veinlets. In the more open parts of the larger veins, the interstices besides being lined with a crust of rashleighite, are filled with soft white china-clay and also a yellowish clay-like substance, and on some specimens the mineral is thickly invested with scaly gilbertite. In other veinlets up to 2 cm. wide it completely encrusts small flat crystals of wolframite which thickly stud both walls and also fills the central portion of the veinlet. More rarely, it invests small lustrous black complex twinned crystals of cassiterite and little radiating aggregates of black tourmaline, or with pearly white rosettes of gilbertite lines cavities in rich crystalline cassiterite. In some cases the rashleighite occurs with no admixed minerals save a little included quartz, and in this massive or colloidal form fills the whole veinlet to a thickness of 2 cm., and it was on this material that Dr. Smythe's analysis was made. Under the microscope the crusts are seen to be minutely mamillary or sometimes stalactitic, the surface of the mamillations being indistinctly crystallized and occasionally showing very minute curved triangular faces.

In recent years I have obtained many good specimens of the mineral by digging into the small dumps close to the shaft upon which stands the ruined pumping-engine house. During the last war a small trial for wolframite was made in the form of a trench and short level on a vein outcrop a little south of the southernmost of the two old pits and in this

also a good deal of rashleighite of a true turquoise-blue colour was found under conditions exactly similar to those already described.

Castle-an-Dinas wolfram mine, St. Columb Major, Cornwall

(Six-inch Ordnance map, Cornwall, 33 SW., 1907.)

Soon after the commencement of mining operations at Castle-an-Dinas in 1918 my attention was attracted to a mineral which at that time occurred sparingly as very thin blue-green crusts on the banded sediment enclosing the lode.[1] As work proceeded the mineral became more abundant and by 1931 I had obtained sufficient material to more or less satisfy me that it was turquoise though the quantity of iron present seemed abnormal. In 1938 I gave a brief mention of the occurrence as an associate of the new mineral russellite.[2] On visiting the mine in February 1939, no. 4 level on the north side of the hill, the then deepest in the mine, had almost reached the granite core of the hill, and a stope above this level laid bare considerable quantities of the blue-green mineral now shown to be rashleighite. The lode at this point was full of loosely packed cavities and though still in the banded sediment, was traversed by parallel granite tongues. The filling consisted of much shattered quartz, often in thin sheets, considerable patches of wolframite, large friable masses of rashleighite, and a good deal of wavellite, brown lithia-mica, and rusty ochre. The colour of the Castle-an-Dinas rashleighite is usually light blue-green and brighter in tint than that of Bunny mine, very rarely it is true turquoise-blue, and occasionally pistachio-green. On many specimens it has an intimate association with wavellite. The commonest form is a light blue-green thin crust, sometimes rippled, and covering considerable areas of the banded sediment, the surface of the crust being composed of minute crystallized spheres, and usually sprinkled with silky-white needle crystals of wavellite; also in a similar form on the quartz-wolframite vein-stuff. Large and practically pure light friable and porous blue-green masses up to 23×20 cm. in size are often intersected by very thin sheets of quartz and associated with yellowish-brown ochre. These masses form very handsome specimens and it was upon this material that Dr. Smythe's analysis was made. Under the microscope they are seen to be composed of

[1] Mention of this as 'an as yet undetermined phosphate of alumina' is made in Min. Mag., 1925, vol. 20, p. 233.

[2] A. Russell, Min. Mag., 1938, vol. 25, p. 54. In an article on the Castle-an-Dinas mine by J. H. Trounson (Mining Mag. London, 1940, vol. 63, p. 20) the mineral is referred to as variscite.

countless minute translucent balls, lightly aggregated, their surface formed of curved triangular crystal faces. In the form of minute ½ mm. light blue-green translucent globules with small white spheres of wavellite on greisen adjoining wolframite-bearing quartz-topaz vein-stuff. The radiating needle crystals of wavellite often penetrate the globules of rashleighite which they support; and owing to the periphery of the wavellite spheres being impregnated with rashleighite they show in section an outer blue-green ring forming very beautiful objects under the microscope. In section the rashleighite spheres present a slightly radiating and concentric structure.

The occurrence of rashleighite in the tin-wolfram lodes traversing granite at Bunny mine and in the wolfram lode at Castle-an-Dinas mine would appear to resemble in some respects the occurrence of turquoise in the tin lodes traversing granite and aplite at Montebras, Creuse, France. Professor A. Lacroix in his description of the Montebras turquoise,[1] which apparently has never been analysed, states that it results from the alteration of amblygonite with which mineral it is intimately associated, its other associates being cassiterite, very rarely wolframite, and often wavellite, in a quartzose vein-stuff. The copper, Professor Lacroix suggests, has been furnished by small quantities of a sulphide in the cassiterite.

[1] A. Lacroix, Minéralogie de la France et de ses Colonies, 1901–1909, vol. 3, pp. 228–229, and 1910, vol. 4, p. 530.

The identification of minerals in boiler deposits. Examples of hydrothermal synthesis in boilers.

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[Read April 1, 1948.]

MANY examples of the hydrothermal synthesis of minerals are scattered throughout mineralogical literature. The present paper has been written to bring to the attention of mineralogists the fact that such hydrothermal syntheses are occurring continually in industrial boilers, particularly when control of water softening procedure is not completely efficient.

The main reasons why chemists in recent years have become interested in the nature of the deposits in boilers is that heat interchange surfaces of boilers must be kept clean for as long as possible, so that a minimum of spare boiler capacity is needed to cope with the periods when such plant has to be shut down for cleaning, and that a boiler can operate with maximum heat interchange efficiency while it is working; moreover, certain types of boiler scales have such low thermal conductivity that metal tubes to which these adhere may become overheated and finally fail.

In order to appreciate the conditions in which deposition of solid phases is occurring, it is convenient to mention that evaporation in boilers takes place at pressures varying from below 100 lb./sq. in. to 2000 lb./sq. in. in the case of the most modern boilers, i.e. at temperatures below 164° and up to 336° C.

The composition of the water entering boilers is extremely variable; thus many high-pressure boilers, particularly those producing power only, are serviced with distilled water containing only the chemicals necessary to reduce corrosion and to deal with possible leakage from condensers: on the other hand, purified water is often used even in high-pressure boilers where steam is needed not only for power production but also for heating: finally, in low-pressure boilers raw water is still sometimes used, but there is a general tendency even at low pressures to use purified water, as the economic advantage of running with clean boilers is usually decisive.

In this paper we are most interested in the results of using raw or chemically treated water in boilers. It is convenient to classify raw waters into three main types:

(*a*) Those derived from limestone or chalk areas, and consequently containing a high ratio of temporary to permanent hardness (200 parts temporary hardness and say 50 parts permanent hardness/10^6).

(*b*) River and lake waters of the Midland counties, containing both temporary and permanent hardness (say 100 parts temporary and 150 parts permanent hardness/10^6).

(*c*) Soft, moorland waters often peaty and consequently slightly acidic in character (up to 50 parts permanent hardness/10^6).

We will deal first with boiler deposits which are likely to be found when raw waters are used without purification. From type (*a*) it is most likely that calcite will be the major constituent of boiler scale, but type (*b*) will generally deposit both calcite and anhydrite; type (*c*) may deposit scales containing anhydrite and a silica-containing phase. Comparatively little detailed work has been done on the nature of deposits formed by raw water, as the industrial problems nowadays arise from purified water evaporation and the main effort has been concentrated on identifying constituents of scales formed from purified water.

It is unnecessary now to discuss the results obtained by various softening processes, but in general purified water may contain the following ions, Na, Ca, Mg, Al, Fe, CO_3, Cl, PO_4, NO_3, SiO_2, SO_4, OH. In addition, traces of Cu, Zn, Ba, Sr may more rarely be present, the two former generally from corrosion of boiler equipment. The presence of organic matter from the raw water should not be overlooked as this may have an effect on the habit of crystalline deposits. This mixture provides ample opportunity for a wide range of insoluble products to separate as concentration proceeds. It will be appreciated that as purified water is being fed into a boiler system approximately steady state conditions exist; thus there is a reservoir of more concentrated solution in the boiler from which the more insoluble salts are being deposited whilst they are being replenished from the incoming feed water; soluble salts would increase in concentration but for the fact that these are controlled by removing a definite proportion of the solution periodically.

The degree of concentration of soluble salts which can be permitted tends to be lower the higher the pressure at which the boiler is operating

and the higher the purity of steam required. To illustrate this point, and to give an idea of the media from which boiler scales separate, the table which follows has been included.

TABLE I. Composition of boiler water in parts per million at various boiler pressures.

Boiler pressure (lb./sq. in.) ...	1350.	880.	800.	800.	625.	180.
Na_2CO_3	34	74	113	86	41	2040
NaOH	83	103	519	156	94	3720
Na_2SO_3	20	25	nil	22	170	nil
Na_2SO_4	1220	185	625	523	401	7280
NaCl	158	6	230	103	335	2980
Na_3PO_4	25	135	61	172	61	nil
$NaNO_3$	?	?	?	?	?	present
SiO_2	8	?	?	41 approx.	18–44	present
Total dissolved solids, approx.	1500	528	1548	1105	1102	16,020

No calcium or magnesium ions were detected.

General method of preventing formation of individual phases.

Perhaps the most commonly occurring substance to be formed is calcite, but as this is somewhat less adherent than other minerals to be mentioned later, and as it is more easily removed either by mechanical or by chemical cleaning, it presents no real difficulty in boiler operation. Anhydrite, however, used to be a quite common constituent of deposits, and as it is definitely harmful, and as the process by which its formation may be inhibited is of general application, perhaps it is worth mentioning in rather more detail. Deposition of $CaSO_4$ will occur when the solubility product $[Ca]^{\cdot\cdot}\,[SO_4]''$ is exceeded in the water concentrating in the boiler, and will tend to take place on the heating surfaces of the boiler because the solubility temperature coefficient ds/dt is negative. If now it is possible to arrange that another and less harmful calcium salt is preferentially formed in place of anhydrite, then the latter should no longer be deposited. In practice this is effected in boilers up to 200 lb./sq. in. pressure by keeping a sufficiently high concentration of CO_3 ions in the concentrating boiler water, because if the relation $[CO_3]/[SO_4]$ is held above a certain value, the solubility product $[Ca][CO_3]$ will then be exceeded and calcite will always be precipitated. Above 200 lb./sq. in. pressure it is more usual to use the PO_4 ion to inhibit the deposition of calcite; hydroxyapatite is then preferentially formed. This procedure was initially suggested by Hall.[1] The practical lower limits for the ratios CO_3/SO_4 up to 150° C. and PO_4/SO_4 up to 350° C. were subsequently

[1] R. E. Hall, Indust. Engin. Chem. (Amer. Chem. Soc.), 1925, vol. 17, p. 283.

fixed by determinations of the solubility of $CaSO_4$ in the presence of calcite or of hydroxyapatite.[1]

Minerals that have been identified.

Though it is thus possible to inhibit the formation of anhydrite, the complexity of the composition of chemically treated feed water ensures that a number of interesting mineral species is likely to be formed in boiler conditions and to be deposited either in the sludge, most of which is removed when the boiler is blown down, or in scale adhering to heating surfaces. Partridge,[2] Powell,[3] and other observers, showed that microscopic and petrological examination was of some value in identifying constituents of boiler scale; normally, however, the crystal sizes in boiler scales are so small and the phases so admixed that optical methods are not always useful. The introduction of the more certain X-ray technique[4] for identification opened the way for a more decisive attack on the problem of the identification of constituents of boiler deposits. As a result of these investigations, a considerable number of minerals has now been identified. The following list compiled from the literature mentioned above, though not exhaustive, gives an indication of the wide range of materials which may be formed in boiler conditions.

Calcium compounds: Portlandite, $Ca(OH)_2$; Calcite, $CaCO_3$; Anhydrite, $CaSO_4$; Hydroxyapatite, $3Ca_3P_2O_8.Ca(OH)_2$; Crestmoreite, $2CaO.2SiO_2.3H_2O$; Hillebrandite, $2CaO.SiO_2.H_2O$; Wollastonite, $CaO.SiO_2$; Xonotlite, $5CaO.5SiO_2.H_2O$.

Magnesium compounds: Brucite, $Mg(OH)_2$; Periclase, MgO; Hydromagnesite, $3MgCO_3.Mg(OH)_2.3H_2O$; Hydrotalcite, $MgCO_3.5Mg(OH)_2.2Al(OH)_3.4H_2O$; Chrysotile, $3MgO.2SiO_2.2H_2O$; Sepiolite, $2MgO.3SiO_2.2H_2O$; Mg hydroxyphosphate, $Mg_3(PO_4)_2.Mg(OH)_2$.

Complex silicates: Acmite, $Na_2O.Fe_2O_3.4SiO_2$; Analcime, $Na_2O.Al_2O_3.4SiO_2.2H_2O$; Cancrinite, $4Na_2O.CaO.4Al_2O_3.2(CO_2,SO_3).9SiO_2.3H_2O$;

[1] F. G. Straub, Bull. Engin. Experim. Station, Univ. Illinois, 1933, no. 261. L. M. Clark and E. Hunter, Journ. Chem. Soc. London, 1935, p. 385. L. M. Clark and W. F. Gerrard, Journ. Soc. Chem. Indust., 1938, vol. 57, p. 295.

[2] E. M. Partridge, Research Bull. Univ Michigan Engin., 1930, no. 15, p. 513.

[3] S. T. Powell, Combustion, New York, 1935, vol. 5, no. 3, p. 15.

[4] L. M. Clark and C. W. Bunn, Journ. Soc. Chem. Indust., 1900, vol. 59, p. 155 [M.A. 8–116]. C. E. Imhoff and L. A. Burkardt, Indust. Engin. Chem. (Amer. Chem. Soc.), 1943, vol. 35, p. 873. H. C. Miller, Proc. Amer. Soc. Testing Materials, 1943, vol. 43, p. 1269. T. C. Alcock, L. M. Clark, and E. F. Thurston, Journ. Soc. Chem. Indust., 1944, vol. 63, p. 292 [M.A. 9–103]. M. Reinhard, E. Brandenberger, and G. Oesterheld, Helvetica Chim. Acta, 1942, vol. 25, p. 336 [M.A. 9–284].

Sodalite group, $3(Na_2O.Al_2O_3).2SiO_2.2NaCl$, &c.; Pectolite, $Na_2O.4CaO.6SiO_2.H_2O$.

Copper compounds: Atacamite, $CuCl_2.3Cu(OH)_2$; Chalcopyrite, $CuFeS_2$; Copper metal.

Laminated boiler scales.

It has been stated above that the constituents of boiler scales are laid down in intimate mixture. Like most generalizations, this statement has limitations, for occasionally a scale is found which is well laminated, and the laminae may then be composed of more or less pure mineral species; presumably this differentiation has been caused by a change in some factor in boiler control, such as a variation in feed-water composition, in the rate of evaporation of steam, or in pressure. If it were possible to have accurate knowledge of such variations and to correlate these with the effects produced, a considerable step would have been taken towards the elimination of some types of deposit. However, so far it has not been possible to do this. As an illustration of a complex laminated boiler scale, reference may be made to a scale taken from a Lancashire boiler operating at 125 lb./sq. in. pressure. This scale was 5 mm. thick: on the side adhering to the boiler wall, there was a translucent layer 1 mm. thick, which was composed almost entirely of cancrinite. Next came a hard layer, 3 mm. thick, which contained a mixture of cancrinite and one of the sodalite minerals (probably nosean), and finally the outer layer in immediate contact with water in the boiler contained calcite and chrysotile.

Several interesting points may perhaps be suggested about the mineral constituents of boiler scales from the observations made in the Northwich Laboratories:

(*a*) Of the ten boiler scales which we have examined containing chrysotile, three also contained pectolite; it is possible that the two phases can separate together over a fairly wide range of composition of boiler water and of temperature variations.

(*b*) It seems possible that some of the more complicated minerals which have been identified are not primary deposition products; thus such materials as cancrinite or the sodalite minerals may be built up by the continued action of higher temperatures in parts of the scale nearest the metal heat-interchange surfaces on simpler initially formed substances in the presence of the various components present in boiler water. It will be appreciated that when a scale is once adhering to a heated metal surface conductivity of the system is reduced, and if the same

rate of heat flow is to take place the temperature of the metal must rise. The formation of secondary products may require the transfer of suitable ingredients from the boiler water through a layer of scale. With some types of scale this seems not impossible as they are somewhat porous, though the diffusion process must be slow. Two examples of the phenomenon may be given. When sodalite and analcime are found in the same scale, the sodalite occurs in a lamina next to the metal, i.e. in the hottest part of the system, the analcime being on the water side of the scale. On the other hand, in the two scales in which we have found cancrinite or sulphatic cancrinite, this mineral has been in contact with the hot metal, whilst nosean with which it has been associated has been in a layer farther away from the hottest zone, though in the example given earlier in this paper there was an intermediate zone in which cancrinite and nosean were admixed.

There is little evidence in the literature about the conditions in which the sodalite minerals or cancrinite can be formed, though Lemberg[1] considered that he had synthesized a member of the group at 200° C., whilst Friedel[2] prepared sodalite by the action of salt and sodium hydroxide on mica at 500° C. It is clear that a good deal of experimental work would be required to confirm the thesis suggested above.

(*c*) From a comparison of the chemical compositions of some boiler scales with the minerals identified therein, it is sometimes difficult to account for the amounts of magnesia shown by the analysis. It is known that calcite may have limiting amounts of magnesium replacing calcium. We have found that in the calcite contained in some scales containing large proportions of magnesia, there is a significant diminution of the cell dimensions of the calcite as revealed by X-ray powder patterns. This diminution would be expected if a proportion of the calcium in calcite had been replaced by magnesium and it is suggested therefore that some of the hitherto unaccounted magnesia in boiler scales occurs in the calcite fraction. It also seems that magnesia can be present as an amorphous phase, for a sample of scale containing periclase was found in the neighbourhood of a burst in a boiler tube which metallurgical examination showed had been locally at a temperature of about 1000° C.; scale taken from adjoining tubes contained 8 % MgO, but there was no evidence from the X-ray powder pattern of the presence of any magnesia-containing mineral. It is suggested that the periclase was formed by the

[1] J. Lemberg, Zeits. Deutsch. Geol. Gesell., 1887, vol. 39, p. 559.
[2] C. Friedel and G. Friedel, Bull. Soc. Franç. Min., 1890, vol. 13, p. 182.

decomposition of amorphous magnesium hydroxide or carbonate originally present in the scale.

(*d*) A basic magnesium phosphate, $Mg_3(PO_4)_2.Mg(OH)_2$ is occasionally found in boiler scales. This does not appear to have been described as a naturally occurring mineral, but its composition has been fixed by synthesis (Alcock, Clark, and Thurston, loc. cit.)

Solubility of xonotlite in water up to 300° C.

The main objective in identifying mineral species deposited in boilers is to find the conditions which will prevent their formation. The normal way of doing this is to eliminate one or more of the constituents from the feed water, or to induce the preferential formation of some more insoluble compound which does not have the harmful effects of the products whose elimination is being attempted, e.g. as indicated earlier in this paper, calcite or apatite are less obnoxious than anhydrite. When the prevention of anhydrite was found to be possible, attention was turned to the constituents of scales containing high proportions of silica, since such scales are harmful in boiler practice. Little was known about the mode of combination of silica in boiler scales at the time our examination began and the isolation of xonotlite from several samples (Clark and Bunn, loc. cit.) suggested that an approach to the problem of preventing the deposition of silica-containing scales might be made on somewhat the same lines as had been successful for anhydrite elimination. The first step in examining the possibility of eliminating harmful phases is to determine their solubility, and preliminary work to determine the solubility of some of the calcium silicate phases was in hand at the beginning of the war but then had to be stopped. It is apparent that the problem is much more complex than was initially appreciated when the wide variety of silica-containing minerals existing in boiler scales was not known, and it now seems unlikely that it would be fruitful to examine the solubility of each of the many silica-containing minerals; the problem in fact will have to be tackled by more empirical methods. However, in view of the almost complete lack of data on solubility of calcium minerals in water at high temperatures, it may be interesting to record the result of a preliminary investigation on the solubility of xonotlite.

The solubility of xonotlite, $5CaO.5SiO_2.H_2O$, in water was determined as described for apatite (Clark and Gerrard, loc. cit.). A synthetic sample of xonotlite was heated for up to 160 hours with water over a range of temperatures between 150° and 300° C. Samples of the

solutions filtered at the experimental temperature were analysed, calcium being determined by titration of the oxalate with permanganate, and silica colorimetrically as the yellow coloured complex silico-molybdate, using a sodium silicate solution as a standard source of silica for comparison. The following results were obtained:

	150°	200°	250°	300°C.
CaO parts/10^6 H_2O	19	18	10	5
SiO_2 „ „	51	65	33	22

Each of these results is the arithmetical mean of determinations in which there was considerable spread, probably because it may be difficult to reach equilibrium in the system CaO–SiO_2–H_2O. Over-great importance should not be ascribed therefore to the increased silica content at 200° C. over that at 150° C. The main trend of the results, however, is quite clear. It shows that xonotlite is incongruently soluble and that the ratio of CaO/SiO_2 in solution decreases with increasing temperature, as does the xonotlite solubility. It appears that during the dissolution a second phase (or series of phases) containing a higher ratio of calcium oxide to silica must be formed as temperature increases, though, of course, in extremely small amounts. This result may be useful to mineralogists who are interested in the deposition of minerals of the xonotlite type.

A simple method for the measurement of the refractive indices of the felspars.

By Miss Olive Robins, B.Sc.

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[Communicated by Dr. A. K. Wells; read April 1, 1948.]

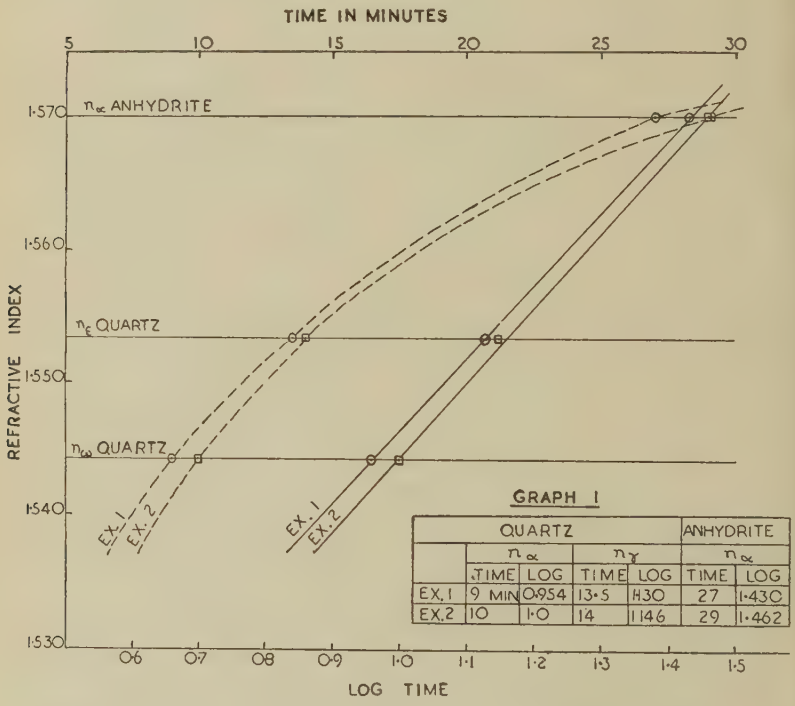
THE method described is one that can be used to measure the refractive indices of minerals when no refractometer is available. The readings are consistent to $\pm 0{\cdot}002$ and are in reasonable agreement with those obtained using a refractometer.

The principle of the method is to mix two liquids with different refractive indices. One of these is a typical immersion liquid with a very low volatility. It must have a refractive index greater than that of the mineral under investigation. The other, more volatile liquid has a refractive index less than that of the mineral. The two liquids selected must be miscible in all proportions, but must not react together. The mineral is completely immersed in a mixture of the two liquids. The more volatile liquid evaporates, and there is a corresponding rise in refractive index. The mineral is kept under observation, and the times when its highest and lowest refractive indices correspond with that of the liquid are noted. The actual value of the indices of the mineral can be read off from a suitable time–refractive index graph.

Technique.—The method can be adapted for use with any mineral, provided that suitable liquids are chosen. The measurement of the refractive indices of the felspars is described here. The anorthite percentage of a plagioclase felspar can be estimated either from the refractive index or from optical measurements made on the universal stage—and this provided a useful means for checking the method.

The liquids used were ortho-toluidine (n 1·570) and toluene (n 1·490), in the proportion of 3 drops of ortho-toluidine to 6 of toluene. This was suitable for felspars with an anorthite content from 20 to 60 %; the proportions would need to be adjusted to deal with felspars outside this range, or with any considerable changes in temperature. The small quantities of liquid required were measured with a glass dropping-pipette into a glass cell—capacity about 0·05 c.c.—made by fusing a glass ring on to a microscope slide.

A number of preliminary experiments were carried out, using minerals of known refractive indices, to determine the rate of evaporation of the mixture, and hence the rate of change of refractive index. These experiments showed that the rate of change of refractive index is a function of the time such that if the refractive index is plotted against the logarithm of the time a straight-line graph is obtained.



GRAPH 1

	QUARTZ				ANHYDRITE	
	n_α		n_γ		n_α	
	TIME	LOG	TIME	LOG	TIME	LOG
EX. 1	9 MIN	0·954	13·5	1·130	27	1·430
EX. 2	10	1·0	14	1·146	29	1·462

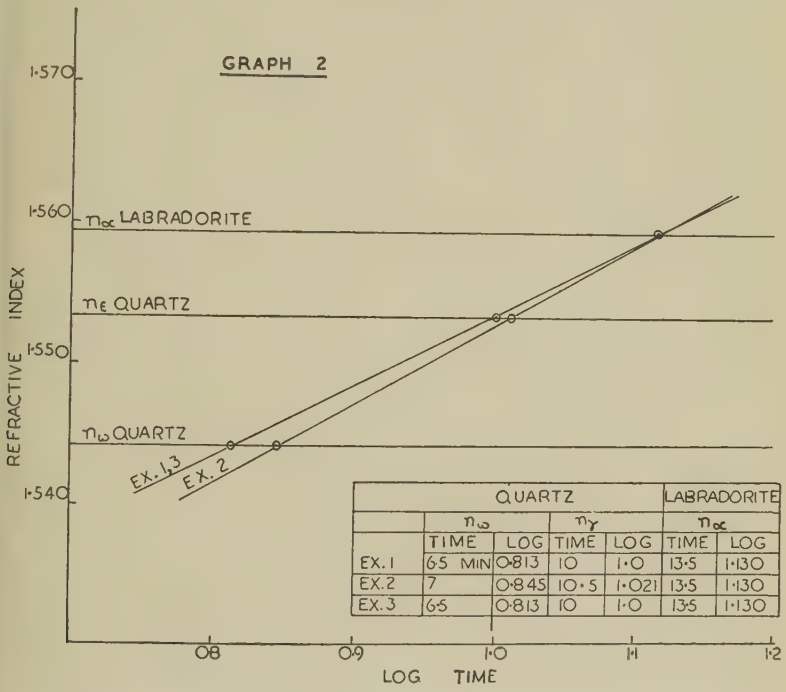
FIG. 1. Evaporation curves with minerals of known refractive indices.

Graphs 1 and 2 (figs. 1 and 2) show the results of two such experiments, using minerals of known refractive indices. The first employed were anhydrite (of which only n_α fell within the range of the liquids used) and quartz. The dotted line shows the curve obtained by plotting refractive index against time in minutes, and the unbroken line the graph of refractive index against log time. The second graph shows a similar linear relationship between quartz and a sample of labradorite on which n_α had been independently determined.

These preliminary experiments showed that readings obtained in the

first three or four minutes after the liquids have been mixed are unreliable. It is advisable therefore to adjust the proportions of the liquids so that the required refractive index range is reached after about five minutes.

The different graphs obtained with successive repeated experiments showed that the small quantities of liquid involved were not being mea-



	QUARTZ				LABRADORITE	
	n_ω		n_γ		n_α	
	TIME	LOG	TIME	LOG	TIME	LOG
EX. 1	6·5 MIN	0·813	10	1·0	13·5	1·130
EX. 2	7	0·845	10·5	1·021	13·5	1·130
EX. 3	6·5	0·813	10	1·0	13·5	1·130

FIG. 2. Evaporation curves with minerals of known refractive indices.

sured very accurately. The rate of evaporation is, in addition, very sensitive to changes in temperature and humidity. It was not possible therefore to construct a standard refractive index–time graph, for use with a given mixture at a specific temperature. To increase the accuracy of measurement would have required more elaborate apparatus, and it was simpler to use instead a 'control mineral', i.e. a mineral with constant chemical composition and known refractive indices which fall within the range of the liquid mixture. Synthetic glasses with suitable refractive indices could equally well be used.

The control mineral is placed in the same cell as the mineral being investigated. The two known refractive indices of the control mineral are observed under the same conditions as those of the undetermined mineral, both minerals being observed in the appropriate extinction positions. The time values of the control mineral are plotted on a refractive index–log time graph, and a straight line drawn between the two points. The refractive index values of the second mineral can then be read off from this graph.

Quartz is an ideal control mineral for the measurement of the felspars. The refractive indices for n_ω and n_ϵ are 1·5442 and 1·553, and, since quartz is a trigonal mineral, both are displayed in a vertical section. A thin section of quartz cut parallel to one of the prism faces and ground down to a thickness of 0·05 mm. was used. This was found to be most suitable, as it was thin enough for accurate measurement, but still thick enough to be easily handled.

The standard refractive index immersion technique uses crushed rock fragments, the assumption being that if a large enough number of randomly orientated fragments are observed some are bound to show n_α and n_γ. The earlier experiments were made with such samples (−100 +150 sieve fraction) and were not very satisfactory. The careful observation of a large number of small fragments is more than usually difficult when there is time factor to contend with. Most minerals fragments have jagged and irregular edges, and it is difficult to observe the Becke line against such edges. Hornblende, for example, with its good prismatic cleavage, gives sharply angular fragments; also it crushes more readily than some of the other common minerals with the result that the final sieve fraction contains a much lower proportion of hornblende than the original rock.

A mineral with a single good cleavage—such as biotite—has thin cleavage fragments which are very suitable for the determination of some of the refractive indices, in this case n_β and n_γ. n_α is seen in a vertical section only; these occur infrequently, and tend to be thick and irregular.

Plagioclase cleavage fragments do not show n_α or n_γ, and allowance is generally made for this when dealing with them. Many rocks containing plagioclase felspars also include quartz and orthoclase or microcline. If the rock is fine-grained it is difficult to separate these, and it is often equally difficult to distinguish between crushed fragments of the several minerals when determining the refractive index of any one.

These were the sort of difficulties experienced with the particular rocks

being investigated. An obvious alternative was to substitute thin sections of rock for the mineral fragments, and this was done with some success. In the method now employed the slice of rock is ground down to a thickness of 0·05 mm., i.e. it is almost twice the thickness of the normal thin section; quartz and felspar then show a maximum interference colour of orange-yellow and yellow respectively. The section is polished, and washed with alcohol until free from Canada balsam. It is then examined under the microscope, and a felspar crystal displaying maximum birefringence selected and broken off. This is placed in the immersion liquid, together with the vertical section of quartz, and the refractive indices of both minerals observed in both positions of extinction. One of the advantages of this method is that the same crystal can be measured as often as required.

If the crystal selected is not correctly orientated to show n_α and n_γ the time difference between the two refractive indices that are observed will be too small. Hence the corresponding anorthite percentages will differ, that for n_α being greater than that for n_γ. This provides a useful check.

Results.—Graphs 3 and 4 (figs. 3 and 4) show the results obtained when single felspar crystals (from the Dalbeattie, Kirkcudbrightshire, 'porphyrites') were investigated by this method. The refractive index results for repetitions of the same experiments do not vary by more than 0·002, and the percentage anorthite values for n_α and n_γ are in reasonable agreement with each other.

The four experiments on each individual crystal were carried out in succession, so that the variation in the shape of the graph is presumably due, not to variation in the external conditions, but to the liquid mixture having a different initial composition. The shift produced by a change in external conditions is shown in graph 4, where the broken line is the graph of one of the experiments of graph 3. It is obvious that the temperature and humidity do have a considerable effect on the shape of the graph, and the use of a control mineral seems to be the only simple way of dealing with this problem.

The results of a number of experiments are summarized in tables I and II. Table I compares results obtained by the evaporation method with values of anorthite percentage estimated by the universal stage, using the same sample of rock, but not the same thin sections. The plagioclase phenocrysts are zoned, and the universal stage results show a variation in anorthite percentage from 25 to 45, with an average value of 30 %. This is in good agreement with the anorthite values

corresponding to the refractive index measurements. Crystal II from rock specimen 59 provides an example of a badly orientated crystal where the extreme refractive index values were not displayed.

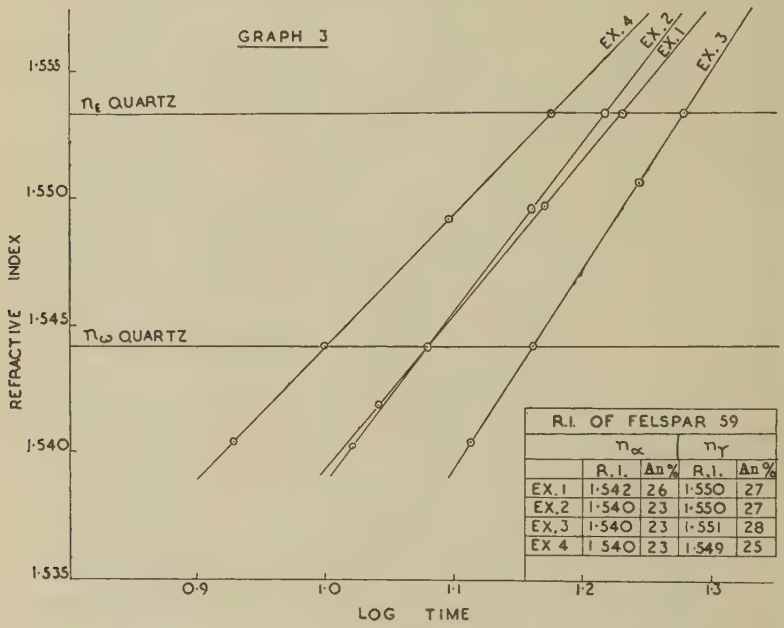


Fig. 3. Evaporation curves with felspars of unknown refractive indices.

Table I. Plagioclase phenocrysts from the Dalbeattie, Kirkcudbrightshire, 'porphyrites'.

Rock.	Refractive index measurements.						Universal stage results.			
	Crystal.	No. of readings.	n_α	% An.	n_γ	% An.	Crystal.	No. of readings.	Anorthite % Range.	Mean.
50	I	3	1·548	38	1·555	37	A	2	—	30
	II	4	1·542	26	1·552	30	B	5	28–40	33
	III	4	1·5405	24	1·550	27	C	4	33–45	37
59	I	4	1·541	25	1·550	27	A	1	—	27
	II	4	1·546	35	1·550	27	B	2	25–29	27
	III	4	1·540	23	1·549	25	—	—	—	—
	IV	4	1·540	23	1·548	24	—	—	—	—

Table II compares results obtained by this evaporation method with those obtained using an Abbe refractometer. In two cases (49, 2 and 49, 3) the same crystal was measured by both methods. The difference

between the values obtained by the two methods ranges from 0·0004 to 0·0035. The discrepancy is probably due in part to the zoning of the crystals. However, the maximum variation between repeated refracto-

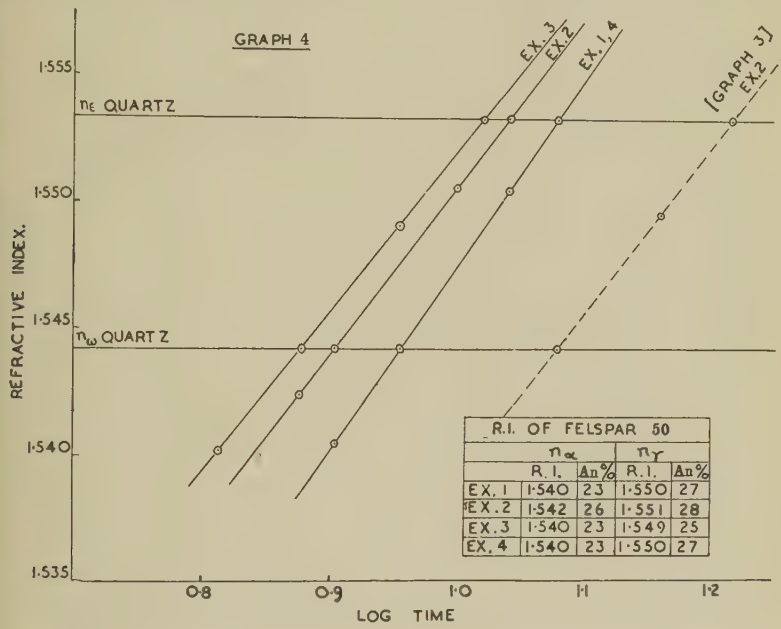


FIG. 4. Evaporation curves with felspars of unknown refractive indices.

TABLE II. Comparison of refractive index values obtained by two methods.

Rock.	Crystal.	Evaporation method.			Refractometer readings.			
		No. of readings.	n_α	n_γ	No. of readings.	n_α	n_γ	Maximum variation.
49	1	4	1·539	1·549	—	—	—	—
49	2	6	1·540	1·550	6	1·5406	1·5465	0·0026
49	3	6	1·540	1·548	4	1·5431	1·5484	0·0024
W. 87	—	3	1·560	1·567	3	1·5594	1·5705	0·0036

meter readings is of the same order of magnitude. It may very well be that improved accuracy of measurement here might lead to closer agreement between the two sets of values.

I wish to thank Professor W. T. Gordon for facilities provided and for supervising this work. I should like also to express my gratitude to Dr. A. K. Wells for the continued interest shown, for much helpful discussion, and for presenting the paper at the meeting of the Society.

The lattice parameters and interplanar spacings of some artificially prepared melilites.

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[Communicated by Dr. F. A. Bannister; read June 24, 1948.]

Introduction.—A laboratory investigation in connexion with some blast-furnace slags, led to the preparation of the five synthetic melilites for which X-ray data are provided. The five compounds represent gehlenite, åkermanite, and three members of the intermediate series of solid solutions, corresponding to 25, 50, and 75 % of åkermanite.

The binary system gehlenite–åkermanite was studied by Ferguson and Buddington,[1] who established relationships between refractive indices, density, and composition and determined solidus and liquidus curves. The crystal structure of the melilite group of compounds was investigated by Warren,[2,3] who showed that the structure was based on a tetragonal lattice. In åkermanite the magnesium atoms occupy the centres and corners of the (001) faces, whilst the silicon atoms are at the centres of silicon–oxygen tetrahedra joined together in pairs by a common oxygen atom, thus forming Si_2O_7 groups. In going from åkermanite to gehlenite magnesium atoms are replaced by aluminium and some of the silicons by aluminium also. The composition of gehlenite is reached when all the magnesium atoms and half the silicon have been replaced in this manner. The replacement may be represented by $Mg^{2+}+Si^{4+} \rightleftharpoons Al^{3+}+Al^{3+}$. We are not here concerned with the similar replacement of Ca+Mg by Na+Al, which would account for the presence of the sodium atoms usually included in the general formula for melilite.

Experimental Work.—The samples were prepared from pure component oxides of 'analytical reagent' or similar quality. The calcium oxide was prepared by calcining calcium carbonate at a temperature of

[1] J. B. Ferguson and A. F. Buddington, The binary system åkermanite–gehlenite. Amer. Journ. Sci., 1920, ser. 4, vol. 50, pp. 131–140. [M.A. **1**–167.]

[2] B. E. Warren, The structure of melilite $(Ca,Na)_2(Mg,Al)_1(Si,Al)_2O_7$. Zeits. Krist., 1930, vol. 74, pp. 131–138. [M.A. **4**–367.]

[3] W. L. Bragg, Atomic structure of minerals. London, 1937, p. 177. [M.A. **7**–7.]

about 950° C., but all oxides were heated at this temperature immediately before weighing out the quantities required. Samples of a total weight of approximately one gram each were prepared. A technique of careful and prolonged mixing and grinding together was followed, and the mixtures then rammed into cylindrical pellets, ready for firing.

TABLE I. Compositions and lattice parameters of standard compounds.

	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.
% Gehlenite	100	75	50	25	0
% Åkermanite ...	0	25	50	75	100
	Molecular percentage composition.				
CaO	50·00	47·06	44·44	42·11	40·00
Al_2O_3	25·00	17·65	11·11	5·26	—
MgO	—	5·88	11·11	15·79	20·00
SiO_2	25·00	29·41	33·33	36·84	40·00
CaO/SiO_2	2·00	1·60	1·33	1·143	1·00
	Weight percentage composition.				
CaO	40·94	41·00	41·04	41·12	41·20
Al_2O_3	37·19	27·96	18·65	9·34	—
MgO	—	3·64	7·41	11·09	14·77
SiO_2	21·87	27·40	32·90	38·45	44·03
	Lattice parameters, kX units.				
a	7·674	7·703	7·738	7·772	7·828
	±0·002	±0·002	±0·003	±0·003	±0·002
c	5·057	5·044	5·034	5·016	5·000
	±0·002	±0·002	±0·003	±0·002	±0·002
c/*a*	$0·659_0$	$0·654_8$	$0·650_5$	$0·645_4$	$0·638_7$
	±0·0004	±0·0004	±0·0006	±0·0005	±0·0004
	Lattice parameters, Ångström units.*				
a	7·690	7·719	7·754	7·787	$7·843_5$
c	$5·067_5$	$5·054_5$	$5·044_5$	$5·026_5$	5·010

* The values in Å. are obtained by multiplying the kX values by a factor of 1·00202.

The compositions of the samples are listed in table I. It is considered that the probable errors in composition arising from the method of preparation employed are less than would be obtained by ordinary chemical analysis of much larger samples. Samples of the size prepared are small enough to be thoroughly mixed by careful hand-mixing, but large enough for the components to be sufficiently accurately weighed, and for the effect of small losses (in any case practically nil) to be negligible in proportion.

The heating schedule was: The samples were heated from 20 to 1300° C. in approximately 4 hours, and then held at 1300° C. for approximately 3 hours, and finally cooled down with the furnace.

The samples were examined by the X-ray powder method in the 9 cm. diameter camera and the photographs which were taken with Co-$K\alpha$ radiation are illustrated in fig. 1. The photographs showed that the crystals were reasonably well developed, and sharp lines were generally

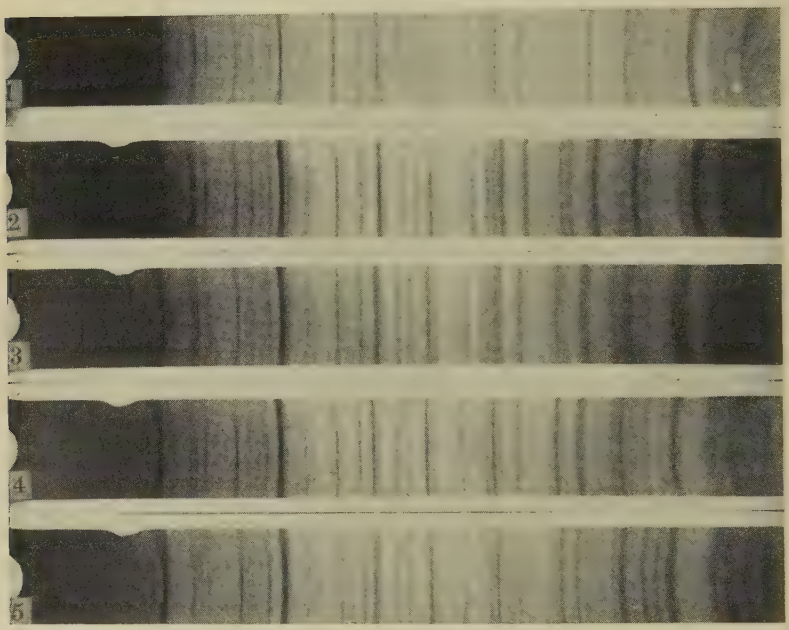


Fig. 1. X-ray powder photographs (reduced from 5 inches) of the two end-members and three mixed crystals of the gehlenite–åkermanite series.

	1.	2.	3.	4.	5.
Gehlenite	100	75	50	25	0
Åkermanite	0	25	50	75	100

obtained up to high angles. The sample representing 50 % gehlenite, and 50 % åkermanite in mutual solid solution (no. 3), however, showed somewhat poorer lines at high angles than the others. No change was observed after prolonged periods of heating with this or the other samples, and the photographs provided the accuracy desired.

The values of the lattice parameters and axial ratios corresponding to the five synthetic samples are included with the composition data in table I. The results are plotted against composition in fig. 2, which shows how, proceeding from gehlenite to åkermanite, the replacement of 2Al by Mg+Si leads to an increase in the a spacing and a decrease in the c spacing, with a corresponding decrease in axial ratio.

Measurements were made in kX units and converted to Ångström units as indicated in table I. The a and c parameters were then used to calculate interplanar spacings which are recorded in table II, together

TABLE II. Values of interplanar spacings in Ångström units.

Indices	No. 1.		No. 2.		No. 3.		No. 4.		No. 5.	
hkl	I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	I	d_{hkl}
101	vvw	4·232	vvw	4·229	vvw	4·228	vw	4·223	vw	4·222
111	wm	3·708	wm	3·708	w	3·712	w	3·712	w	3·717
210	vvw	3·439	vvw	3·452	vvw	3·468	vvw	3·483	vw	3·508
201	wm	3·063	wm	3·067	wm	3·074	m	3·078	m	3·088
211	s	2·846	s	2·851	s	2·858	s	2·863	s	2·874
220	vvw	2·719	vvw	2·736	vvw	2·742	vvw	2·753	—	—
002	vvw	2·534	vvw	2·527	vvw	2·522	vvw	2·513	vvw	2·505
310	m	2·432	m	2·441	m	2·452	m	2·463	m	2·480
102	m	2·407	m	2·402	w	2·399*	wm	2·392*	wm	2·386*
221		2·396		2·401	wm	2·409*	w	2·415*	w	2·426*
112	m	2·297	m	2·293	vw	2·291*	vw	2·286*	w	2·283*
301		2·287		2·293	wm	2·300*	wm	2·306*	wm	2·318*
311	vw	2·193	vw	2·198	vvw	2·205	vvw	2·211	vvw	2·223
202	vvw	2·116	vvw	2·114	vvw	2·114	vvw	2·112	vvw	2·111
212	wm	2·040	wm	2·039	wm	2·040	m	2·038	m	2·039
321	vw	1·966	vw	1·971	vvw	1·978	vw	1·984	vw	1·996
400	wm	1·922	wm	1·930	wm	1·939	wm	1·947	wm	1·961
410	w	1·865	w	1·872	w	1·881	w	1·889	wm	1·902
222	w	1·854	vw	1·854	vw	1·856	vw	1·856	vw	1·859
330	wm	1·813	wm	1·819	wm	1·828	wm	1·836	wm	1·849
312	s	1·755	s	1·756	ms	1·758*	ms	1·759*	ms	1·763*
411		1·752		1·756		1·762*	wm	1·768*	wm	1·779*
420	w	1·720	w	1·726	vw	1·734	vw	1·741	—	—
331	vvw	1·707	vvw	1·712	vw	1·718	vw	1·724	w	1·734
003	—	—	vvw	1·685	vvw	1·682	vvw	1·675	vvw	1·670
322	w	1·632	w	1·634	w	1·636*	w	1·638*	w	1·643*
421		1·628		1·633		1·640*		1·645*	vvw	1·655*
113	vw	1·613	vw	1·610	vw	1·608	w	1·603	w	1·599
203	vvw	1·547	vvw	1·544	vvw	1·543	vw	1·539	vw	1·537
412	—	—	—	—	—	—	—	—	vw	1·515
213	m	1·516	m	1·514	m	1·513	m	1·510	wm	1·508
332	vw	$1·474_5$	vw	$1·476_5$	vw	1·480	vw	1·482	vw	$1·487_5$
511	vvw	$1·445_5$	vvw	$1·450_5$	vvw	1·456	vw	$1·461_5$	w	$1·470_5$
520	—	—	—	—	—	—	—	—	vvw	$1·456_5$
223	w	1·435	w	$1·433_5$	wm	$1·433_5$	wm	$1·431_5$	wm	1·431*
422	vw	1·423	vvw	$1·425_5$	vw	1·429		$1·431_5$		$1·436_5$*
303	vvw	$1·410_5$	vvw	$1·409_5$	vw	$1·409_5$	vw	$1·407_5$	w	$1·407_5$
313	vw	$1·387_5$	vw	$1·386_5$	vw	$1·386_5$	vvw	1·385*	vvw	$1·385_5$*
521	m	$1·374_5$	m	1·379	m	$1·384_5$	m	1·390*	m	$1·398_5$*
440	w	$1·359_5$	w	$1·364_5$	vw	1·371	w	$1·376_5$	w	$1·386_5$*

I intensity: s strong, m medium, w weak, &c.
* Lines whose relative positions are reversed by axial ratio change.

with the corresponding indices and relative intensities. These calculated interplanar spacings are expected to be useful for the identification of members of this series of solid solutions. The actual calculated values are retained (rather than a mean value) where two lines are too close together to be resolved. It will thus be observed how some pairs of lines

such as 102 and 221, or 312 and 411, approach, coincide, and then separate on the opposite side of each other, as the axial ratio changes

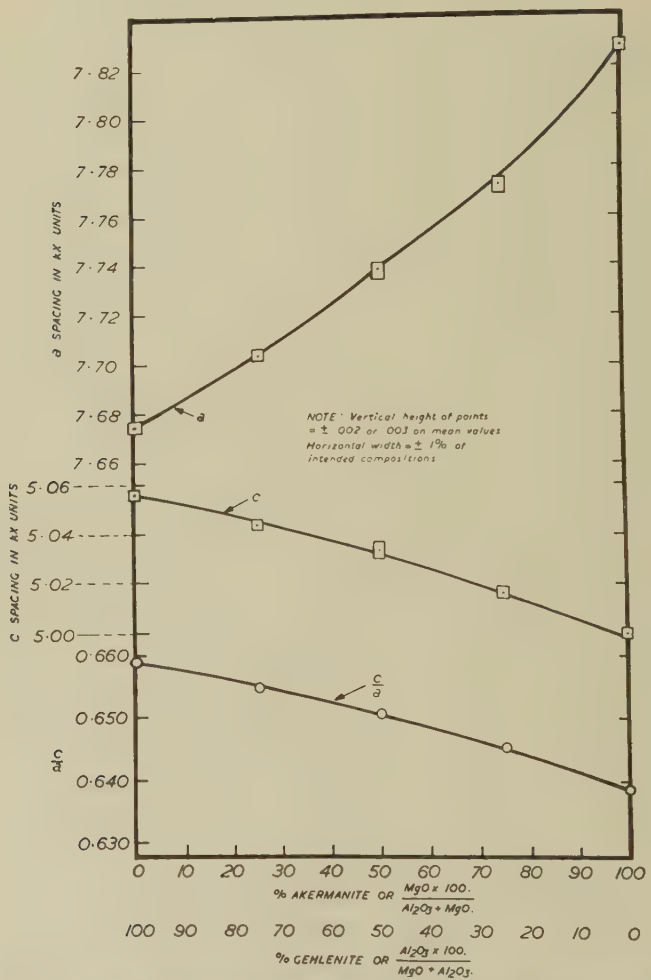


FIG. 2. Lattice spacing relationships in the gehlenite–åkermanite series.

from one end of the series to the other. Lines which as a result are displaced in the otherwise strict order of decreasing magnitude of d_{hkl} in the table, are therefore indicated by an asterisk.

Conclusions.—The five members of the solid solution series examined have been sufficient to indicate to a reasonable degree of accuracy the

lattice parameter variations accompanying the isomorphous substitution represented by $Mg+Si \rightleftharpoons Al+Al$. The ionic radii are in the order Mg $>$Al$>$Si, and commencing with åkermanite the replacement of Mg by Al would be expected to lead to a contraction of the lattice, whilst the replacement of some of the Si atoms by Al would result in an increase in the dimensions of the silicon–oxygen tetrahedra linked in pairs. The combination of these two tendencies leads to the resultant decrease of the *a* parameter and increase of the *c* parameter proceeding from åkermanite to gehlenite (i.e. from right to left in fig. 2).

Interplanar spacing data are provided, and are expected to be of use for the identification of members of this series of solid solutions, providing that isomorphous substitution of ions other than those considered is not large enough to affect the spacings seriously. The presence of sodium ions in melilites has been referred to in the introduction. The replacement of magnesium by divalent iron (and possibly also by manganese) and of aluminium by trivalent iron is expected. In the mineral hardystonite $Ca_2ZnSi_2O_7$ the Mg of åkermanite is completely replaced by zinc. The possibility of other substitutions is not excluded providing the ionic radii are of a similar order to the radii of the ions referred to.

Acknowledgements.—The author wishes to thank Mr. F. H. Saniter, Director of Research, The United Steel Companies Limited, for permission to publish these data. He would also like to record his gratitude to the late Dr. A. H. Jay under whose direction the work was commenced, and his thanks to Mr. N. Marshall for assistance with some of the calculations.

Pyroxene from the Squilver dolerite, south Shropshire.

By F. G. H. Blyth, M.Sc., F.G.S.

Geology Department, Imperial College of Science and Technology, London.

[Read June 24, 1948.]

THE andesine-dolerite of Squilver Hill, situated nearly 3 miles due north of Bishops Castle, has been described in another place.[1] This somewhat coarse-textured rock, with a distinctive greenish-blue colour, contains up to 20 per cent. of a fresh monoclinic pyroxene as crystals of irregular shape, many of which are about a millimetre in length. The rest of the rock consists of saussuritized plagioclase, some interstitial chlorite and prehnite, and accessory apatite, sphene, magnetite, and ilmenite; the unaltered nature of the pyroxene is noteworthy.

The pyroxene was separated from the crushed rock by the use of bromoform and methylene iodide; the grains passed a 60-mesh sieve and at no stage did they come into contact with water before analysis. The larger grains of the final sample were hand-picked in order to avoid including any that were obviously composite. The composition of the mineral together with its optical data, specific gravity, and formula calculated to a basis of O = 12, are given in table I. The analysis of the dolerite from which the pyroxene was obtained is given in table II and has been reproduced by permission of the Council of the Geological Society of London.

The pyroxene is a diopsidic augite; it has a small content of aluminium, the greater part of which is substituted for silicon in the crystal structure. When molecular proportions of Wo, En, and Fs are computed and plotted in the usual triangular diagram, the point obtained falls within the salite field as defined by Hess[2] and Poldervaart.[3]

The chemical analysis, however, shows a water content of 1·70 % (H_2O+); many pyroxene analyses show up to 0·5 % of water, in some cases more, which is rarely commented upon. In the present case the water might be accounted for in various ways: (i) it may be due to

[1] F. G. H. Blyth, Intrusive rocks of the Shelve area, south Shropshire. Quart. Journ. Geol. Soc. London, 1944, vol. 99 (for 1943), pp. 169–204.

[2] H. H. Hess, Amer. Min., 1941, vol. 26, pp. 515, 573. [M.A. 8-233.]

[3] A. Poldervaart, Min. Mag., 1947, vol. 28, p. 159.

chlorite associated with the pyroxene; (ii) it may (in part) be water adsorbed on the surface of cracks in the mineral; or (iii) the pyroxene may be hydrous. This last possibility is not borne out by considerations of specific gravity. Thin sections of the dolerite reveal that some of the

TABLE I. Analytical and optical data.

(Analysis by Geochemical Laboratories.)

		Atomic ratios.	Atomic ratios after deduction for chlorite.	Number of atoms when O = 12.	
SiO_2 ... ... 48·50	$Si^{\cdots\cdot}$ 0·8075	0·7367	3·822		
Al_2O_3... ... 4·50	$Al^{\cdots}$ 0·0883	0·0411	0·213	0·178	4·000
				0·035	
Fe_2O_3... ... 1·36	$Fe^{\cdots}$ 0·0170	0·0170	0·088		
FeO ... ... 8·18	$Fe^{\cdot\cdot}$ 0·1139	0·0864	0·448		
MgO ... ... 15·06	$Mg^{\cdot\cdot}$ 0·3735	0·2831	1·469		
CaO ... ... 19·32	$Ca^{\cdot\cdot}$ 0·3445	0·3445	1·787		
Na_2O ... ... 0·32	$Na^{\cdot}$ 0·0103	0·0103	0·053		3·992
K_2O ... ... 0·17	$K^{\cdot}$ 0·0036	0·0036	0·019		
H_2O+ ... 1·70	$Ti^{\cdot\cdot\cdot\cdot}$ 0·0134	0·0134	0·070		
H_2O- ... 0·15	$Mn^{\cdot\cdot}$ 0·0042	0·0042	0·022		
TiO_2 ... ... 1·07	$Cr^{\cdots}$ 0·0001	0·0001	0·001		
MnO ... ... 0·30	$H^{\cdot}$ 0·1887	—	—		
Cr_2O_3... ... 0·01	O'' 2·7374	2·3129	12		
BaO ... ... nil					
100·64					

Formula: $(Ca,Mg,Fe^{\cdot\cdot},Na,K,Ti,Mn,Fe^{\cdots},Al)_2(Si,Al)_2O_6$.
Colour of grains: pale green. Specific gravity 3·38.
Refractive indices: α 1·673, β 1·678, γ 1·705. $\gamma-\alpha$ 0·032.
2V 48–49°, positive. γ: c 42°.
Weight % (neglecting sesquioxides, titania, and alkalis): Wo = 49·8, En = 35.4, Fs = 14·8

TABLE II. Analysis of dolerite, Squilver Hill quarry.

SiO_2 ... 49·19	K_2O ... 0·91		
Al_2O_3 ... 19·47	H_2O+ ... 3·63		
Fe_2O_3 ... 2·35	H_2O- ... 0·16		
FeO ... 5·04	TiO_2 ... 1·00		
MgO ... 4·48	P_2O_5 ... 0·30		
CaO ... 8·67	MnO ... 0·11		
Na_2O ... 4·48	CO_2 ... 0·01	Total 99·80	

pyroxene grains, although themselves fresh, enclose small crystals of an earlier mineral phase now pseudomorphed by chlorite, which may represent an earlier pyroxene. The total amount of the chlorite pseudomorphs is small, but their presence probably largely accounts for the water shown by analysis, and this explanation is regarded as more

probable than either of the others mentioned above. Further, a rough estimate from thin sections of the proportion of the chlorite relative to pyroxene gives a result of the right order of magnitude. In calculating the formula of the pyroxene, therefore, a clinochlore composition has been assumed for the chlorite, and the necessary amounts of its constituents, including hydroxyl, have first been deducted, as shown in table I.

Measurements of 2V and $\gamma : c$ were made on thin sections with the universal stage. In obtaining the extinction angle Burri's method[1] was first used, but the results showed considerable variation even on carefully selected sections: eight determinations gave a range from 30 to 45°, four values being less than 40°. An alternative method, described by Turner[2] and due to Nemoto,[3] involves measurements on twin crystals; this method was eventually used, several suitably sectioned twins being available, and gave consistent results.

Refractive indices were determined by immersion of grains in mixtures of methylene iodide and α-monobromonaphthalene, the values being read with a Bellingham and Stanley refractometer. Specific gravity was obtained from Clerici solution diluted to match the density of grains of the pyroxene immersed in it.

Comparisons and discussion.—For purposes of comparison, the composition (in terms of Wo, En, and Fe) and optical properties of two other pyroxenes are tabulated with the Squilver pyroxene in table III. The

Table III. Comparison with other pyroxenes.

	Wo.	En.	Fs.	2V.	$\gamma : c$.	α.	β.	γ.	$\gamma - \alpha$.
A. ...	49·8	35·4	14·8	48°	42°	1·673	1·678	1·705	0·032
B. ...	46·8	34·2	19·0	52°	44°	1·699	1·706	1·722	0·023
C. ...	46·6	34·0	19·4	43°	41°	1·695	1·702	1·722	0·027

A. Pyroxene from the Squilver dolerite (this paper).

B. Pyroxene IIIA, from olivine-trachybasalt, Pallas Grean, Co. Limerick (D. F. Ashby, Min. Mag., 1946, vol. 27, p. 196).

C. Pyroxene IA, from hypersthene-olivine-gabbro (4077), Skaergaard intrusion, Greenland (L. R. Wager and W. A. Deer, Meddel. om Grønland, 1939, vol. 105, no. 4, p. 77. [M.A., 8–27.]).

three minerals have similar compositions but considerable differences in refractive index and 2V.

Curves for optical properties drawn on a composition diagram have

[1] C. Burri, Schweiz. Min. Petr. Mitt., 1931, vol. 11, p. 285. [M.A. 5–71.]

[2] F. J. Turner, Amer. Journ. Sci., 1942, vol. 240, p. 571. [M.A. 8–350.]

[3] T. Nemoto, Journ. Fac. Sci. Hokkaido Univ., 1938, ser. 4, vol. 4, p. 107.

been given by Winchell,[1] Wager and Deer,[2] and others. The value of 2V for the Squilver pyroxene (A), as read from such curves, is too high when compared with the measured value; this is true also of pyroxenes B and C, table III. There is less discrepancy in refractive index values, in the case of pyroxene A.

The discrepancies in 2V may be attributed to the influence of constituents such as Al, Fe···, Ti, which are present in the minerals, but are not taken into account when the composition is expressed in terms of Wo, En, and Fs. Thus, Winchell (1935, loc. cit.) states that variation in optical properties from those shown in his diagram indicates differences in composition, for example, the presence of alumina; he adds that alumina has little effect on the optic angle and refractive indices but considerable effect on extinction angle. This does not seem to be borne out in the three cases quoted above.

A consideration of the available data, which is scanty, leads the writer to suggest tentatively that differences in 2V (between measured values and those estimated from the curves) may be explainable by reference to that part of the Al which is *not* in 4-co-ordination positions in the crystal structure, together with Fe···,—as distinct from the total (Al,Fe···)-content of the minerals. But it is difficult to establish this definitely until more analyses of pyroxenes of similar composition are available.

Finally, when the proportions of CaO, MgO, and FeO in the Squilver pyroxene and in the rock in which the mineral occurs are compared, it is apparent that the pyroxene is richer in CaO than the rock-melt from which it separated. Such a relationship was pointed out by Kennedy[3] as indicating an olivine-basalt magma parentage, in contrast to a tholeiitic magma, which yields a pyroxene poorer in lime. The affinities of the Squilver dolerite with rocks of olivine-basalt type have already been demonstrated (Blyth, loc. cit.).

Acknowledgements.—The cost of the chemical analysis was defrayed from a Royal Society grant, which is here acknowledged. The author also wishes to thank Dr. W. Campbell Smith for help in connexion with the refractive index determinations.

[1] A. N. Winchell, Amer. Min., 1935, vol. 20, p. 562. [M.A. 6–294.]
[2] L. R. Wager and W. A. Deer, Min. Mag., 1938, vol. 25, p. 15.
[3] W. Q. Kennedy, Amer. Journ. Sci., 1933, ser. 5, vol. 25, p. 239.

The application of phase-contrast microscopy to mineralogy and petrology.

[With Plates XXII–XXIV.]

By Frank Smithells, B.Sc., F.G.S., F.R.M.S.

[Read June 26, 1946.]

Introduction.

PHASE-CONTRAST methods in microscopy appear to have been developed mainly with the intention of applying them to biological subjects, and their application to the examination of mineral substances has received only slight attention.[1–4] This method of study (carried out in a transmitted-light microscope) has a technically strange appearance and it does not take long to realize that a mineral section as shown up under (say) oil and crossed nicols looks very different when viewed under an ordinary or a polarizing microscope. A considerable amount of work must be carried out before it is possible to assess the value of the new instrument for petrological purposes or to interpret all the phenomena observed by its use. Nevertheless, it seems fitting to set out the following short account as a contribution towards this knowledge.

It is not proposed to discuss here the theory or detailed construction of the phase-contrast microscope, the literature on which is already extensive.[1–4,6–8] The present work has been carried out with phase-contrast equipment made by Messrs. Unilux, Dowglass & Simmons. For each of the four objectives (× 16, × 32, × 95, × 97) there is provided an annular diaphragm which may be brought into position beneath the condenser and a phase-retarding plate fitted in the back focal plane of the objective with an annular diaphragm, producing a phase difference

[1] A. B. Bennett, H. Hurwitz, R. Lindenberg, and G. W. Richards, 'Phase microscopy: Theory, Image Effects, Specimen Tests,' Journ. Applied Physics, vol. 16, pp. 20–39.

[2] F. Smithells, 'Phase-contrast microscopy for mineralogy,' Science, London, Feb., vol. 146, p. 67.

[3] F. Zernike, 'Phase contrast, a new method for the microscopic observation of transparent objects,' Physica, Amsterdam, 1942, vol. 9, pp. 686–698, 974–986.

[4] C. R. Burch and J. F. Stock, 'Phase-contrast microscopy,' Journ. Sci. Instruments, 1942, vol. 19, pp. 71–75.

[6] E. T. Dixon, 'Image formation in phase-contrast microscopy,' Journ. Sci. Instruments, 1945, vol. 22, pp. 102–105.

[illegible] [illegible] [illegible] [

indication of its refractive index. According to descriptions in students' text-books, if the mean refractive index differs by less than about 0·1 from that of balsam the relief can generally be described as 'moderate', while a difference of 0·2 gives 'high' or 'very high' relief. With phase-contrast these appearances occur with very much lower refractive index differences. For example, sanidine and microcline with a difference from balsam of about 0·02 and leucite (fig. 3) with a difference of about 0·03, all show speckling which should probably be attributed to surface roughness; apatite (difference about 0·10) shows very pronounced speckling.

Evidence of the results of stress.—Evidence that a grain of quartz has been subjected, at some time during its history, to great stresses is often given by strain shadows, seen when the section is rotated between crossed nicols. This type of deformation is *not* revealed by phase-contrast, but sections which show these strain shadows sometimes show a kind of banding which can be detected with ordinary illumination, as a series of rather feeble parallel Becke lines lying within the grain and moving as the microscope is racked up and down. A section of such a grain viewed with phase-contrast and correctly focused shows a series of light and dark parallel lenticular bands (fig. 4).

Heterogeneity.—Where there is heterogeneity of composition within a mineral resulting in slight differences of refractive index in adjacent parts, the phase-contrast microscope should reveal this feature in light and shade. Zoning of felspars, for example, may show itself as an alternation of light and dark bands (pl. XXIII, figs. 13 and 14); and structures in serpentine may be shown up with enhanced clearness. When the composition is homogeneous, but consists of minute particles of a mineral (e.g. in the kaolin in figs. 5 and 6), a speckled appearance may result, somewhat resembling that due to roughness of surface.

Phase-contrast plus single polarizer.

In the work to be described, polaroids or nicols were used on the instrument with a view to making it a combined polarizing and phase-contrast microscope. Such an instrument is not to be confused with phase-contrast microscopes in which polaroid is used in the construction of the equipment which produces and controls the phase difference.[1,2,3]

[1] Zeiss Catalogues.

[2] E. W. Taylor, The control of amplitude in phase-contrast microscopy. Proc. Roy. Soc. London, Ser. A, 1947, vol. 190, pp. 422–426.

[3] H. Osterberg, The polanret microscope. Journ. Opt. Soc. Amer., 1947, vol. 37, pp. 726–730.

The writer (loc. cit., 1946) has pointed out that, in the examination of thin sections of rocks under the phase-contrast microscope, an improvement of the image may result from polarizing the beam. It is easy to see how this is possible. If a birefringent mineral (1·55 and 1·53, mean 1·54) is in Canada balsam (n 1·54) no clear outline will be seen. With a polarizer suitably orientated, a refractive index difference as great as 0·01 may be produced and may be detected by means of phase-contrast. If the refractive indices of the mineral are, say 1·59 and 1·53 (mean 1·56) the insertion of a polarizer may reduce the refractive index difference from 0·02 to 0·01 or increase it to 0·05. Hence, orientation of the polarizer is of importance, and in a rock section it is usually impossible to improve all parts of the field at the same time. Nevertheless, the changes which occur as the polarizer or the stage is rotated provide information about the optical properties of the minerals present.

'*Twinkling*'.—The 'twinkling' shown by many of the carbonate minerals mounted in Canada balsam when rotated relative to the vibration plane of polarized light is well known. In mounts of mineral grains it shows itself chiefly as a change in the boldness of outline; in sections the change of apparent roughness of surface is a conspicuous feature. The condition necessary for a mineral to show this phenomenon clearly with an ordinary polarizing microscope is that the mineral should possess one refractive index near to that of Canada balsam and another differing by at least 0·10. Using a single polarizer on the phase-contrast microscope the phenomenon is distinctly seen in minerals with much lower birefringence. For example, transverse sections of muscovite (refractive index for light vibrating normal to cleavage 1·55; parallel to cleavage 1·58 to 1·59) shows change of apparent roughness very conspicuously (pl. XXII, figs. 7 and 8). Changes in boldness of outline have been observed with grains of scapolite (pl. XXIII, figs. 9 and 10), cancrinite, oligoclase, and quartz. Grains of chalcedony (crushed carnelian) showed clear textural detail in one position, but lack of it after a rotation of 90°; grains of flint showed no such change. This difference of behaviour between the two minerals is to be attributed to a more or less parallel orientation of particles in the former case and a random orientation in the latter.

Inclusions and intergrowths.—The change in clearness of boundaries which results when a single polarizer is introduced is most noticeable with associations of birefringent minerals whose mean refractive indices are almost identical. Thus, inclusions of one felspar in another may sometimes be made clearer by an appropriately oriented polarizer.

Examples of myrmekite (intergrowth of quartz and plagioclase felspars) have been observed in which contrast between the two minerals can be varied by changing the orientation of the polarizer (pl. XXIV, figs. 11 and 12).

Phase-contrast plus polarizer and analyser.

Perhaps the chief advantage of working with the combined polarizing and phase-contrast microscope is the opportunity it affords of changing over from the phase-contrast to the crossed-nicol effect in order to carry out the established tests for the identification of minerals, and so to correlate the new information with the old. It is, however, sometimes advantageous to observe the effect of phase-contrast plus crossed nicols or of phase-contrast plus parallel nicols, or of either of these combinations with the further addition of a gypsum or a mica plate. The uses of these methods have not been fully explored, but it has been noticed that they sometimes give clearer and sometimes less clear images than those obtained with crossed nicols alone.

Pl. XXIII, figs. 15 and 16 show a case in which the zoning of a plagioclase felspar was rendered much more distinct by using phase-contrast plus crossed nicols than with crossed nicols alone. The image obtained by using phase-contrast without crossed nicols (fig. 14) is perhaps the clearest of all, but the addition of crossed nicols enables the relationship of the zoned felspar to the surrounding grains to be more clearly seen.

Conclusion.

It should perhaps be emphasized that, in phase-contrast microscopy, when two adjacent parts of the field containing the image of a perfectly transparent object differ in intensity, all that can be concluded from this fact is that there must be a small difference in optical path through the corresponding parts of the object. This difference in path may be due to:

(*a*) differences in thickness (e.g. roughness of surface of section),

(*b*) difference in composition (e.g. two different minerals or varieties, giving difference in refractive index),

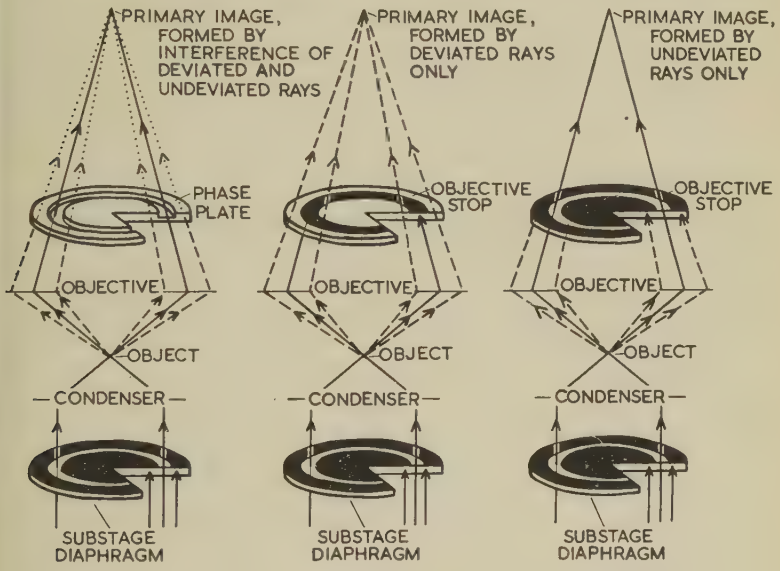
(*c*) difference in optical orientation (giving difference in refractive index). This applies only when polarized light is used.

It is not always easy to identify the actual causes. Contrast due to roughness of surface is enhanced by focusing on the surfaces of the section rather than on the detail lying between them, and such contrast can be made to disappear by immersion in a liquid of appropriate refractive index. Contrast due to roughness of surface may conceal other detail and such immersion may clarify detail due to other causes.

Opaque particles are less clearly seen by using phase-contrast than by using the ordinary methods of microscopy, as can be seen by comparing the following photomicrographs: fig. 5 with fig. 6; fig. 13 with fig. 14; fig. 15 with fig. 16.

Contrast methods not involving phase difference.

Most phase plates are treated with some opacifying substance intended to alter the ratio of intensities of the deviated and undeviated



TEXT-FIG 1. Optical systems for producing contrast.

(*a*) Phase-contrast. (*b*) System 0A. (*c*) System ∞B.

Rays undeviated by the object are shown as unbroken lines, deviated rays as broken lines, rays retarded by the phase plate as dotted lines.

rays. A. H. Bennett *et al.* have explored the possibilities of this treatment very fully. In attempting to repeat some of their work the writer was led to the view that the contrast was in some cases due to refraction at boundary planes between minerals in the object, and that complete opacification of an appropriate area of the plate should lead to still greater contrast in these cases. Hallimond[1] has drawn attention to the

[1] A. F. Hallimond, Production of contrast in the microscope image by means of opaque diaphragms. Nature, London, 1947, vol. 159, pp. 851–852.

fact that refraction phenomena have been neglected in phase-contrast theory and that contrast can be developed by means of stops alone. The objective annuli used by the writer appear to differ from those used by Hallimond in that they correspond exactly in apparent form (as viewed, in position, through the auxiliary microscope) with the substage diaphragm and are of two types as shown in text-fig. 1:[1]

0A Blackened annulus corresponding to the transparent annulus of the substage diaphragm.

∞B Transparent annulus corresponding to the transparent annulus of the substage diaphragm.

Images obtained with these methods and with positive phase contrast are shown in pl. XXIV, figs. 17–20. The conclusion to be drawn from them is not that one method is better than another, but that each emphasizes different features, as follows:

Ordinary illumination: Small opaques.

Type 0A: Microcline-plagioclase boundaries, cleavage, dust particles.

Type ∞B: Microline-plagioclase boundaries.

Positive phase-contrast: Detail within the felspar areas (roughness of surface of section?).

Explanation of Plates XXII–XXIV.

Phase-contrast photomicrographs.

Plate XXII.

Fig. 1. Muscovite flake in medium of lower refractive index. Phase-contrast. ×150.

Fig. 2. Muscovite flake in medium of higher refractive index. Phase-contrast. ×150.

Fig. 3. Leucite, in leucitophyre, Naples. Focused on surface of section. Phase-contrast. ×100.

Fig. 4. Quartz in Ordovician grit, Co. Dublin, showing effects of pressure. Phase-contrast. ×60.

Fig. 5. Keuper sandstone, Yorkshire. Ordinary illumination, stopped down. ×100.

Fig. 6. Same field, showing intersticial kaolin. Phase-contrast. ×100.

Fig. 7. Muscovite in Leinster granite. Phase-contrast. Single nicol, vibration direction E.–W. ×50.

Fig. 8. Same field. Vibration direction N.–S. ×50.

[1] The symbols used are based on those used by A. H. Bennett *et al.* (1946, loc. cit.). They use the letter A when the deviated light is partially suppressed and B when the undeviated light is partially suppressed. Numbers preceding A and B represent the ratio *intensity of deviated light/intensity of undeviated light.*

PLATE XXIII.

FIG. 9. Scapolite, Canada. Phase-contrast. Single nicol, vibration direction E.–W. ×60.

FIG. 10. Same field. Vibration direction N.–S. ×60.

PLATE XXIV.

FIG. 11. Myrmekite in Leinster granite. Phase-contrast. Single nicol, vibration direction E.–W. ×75.

FIG. 12. Same field. Vibration direction N.–S. ×75.

PLATE XXIII.

FIG. 13. Zoned plagioclase in Aughrim granite, Co. Wicklow. Ordinary illumination, stopped down. ×150.

FIG. 14. Same field. Phase-contrast. ×150.

FIG. 15. Same field. Crossed nicols. ×150.

FIG. 16. Same field. Phase-contrast. Crossed nicols. ×150.

PLATE XXIV.

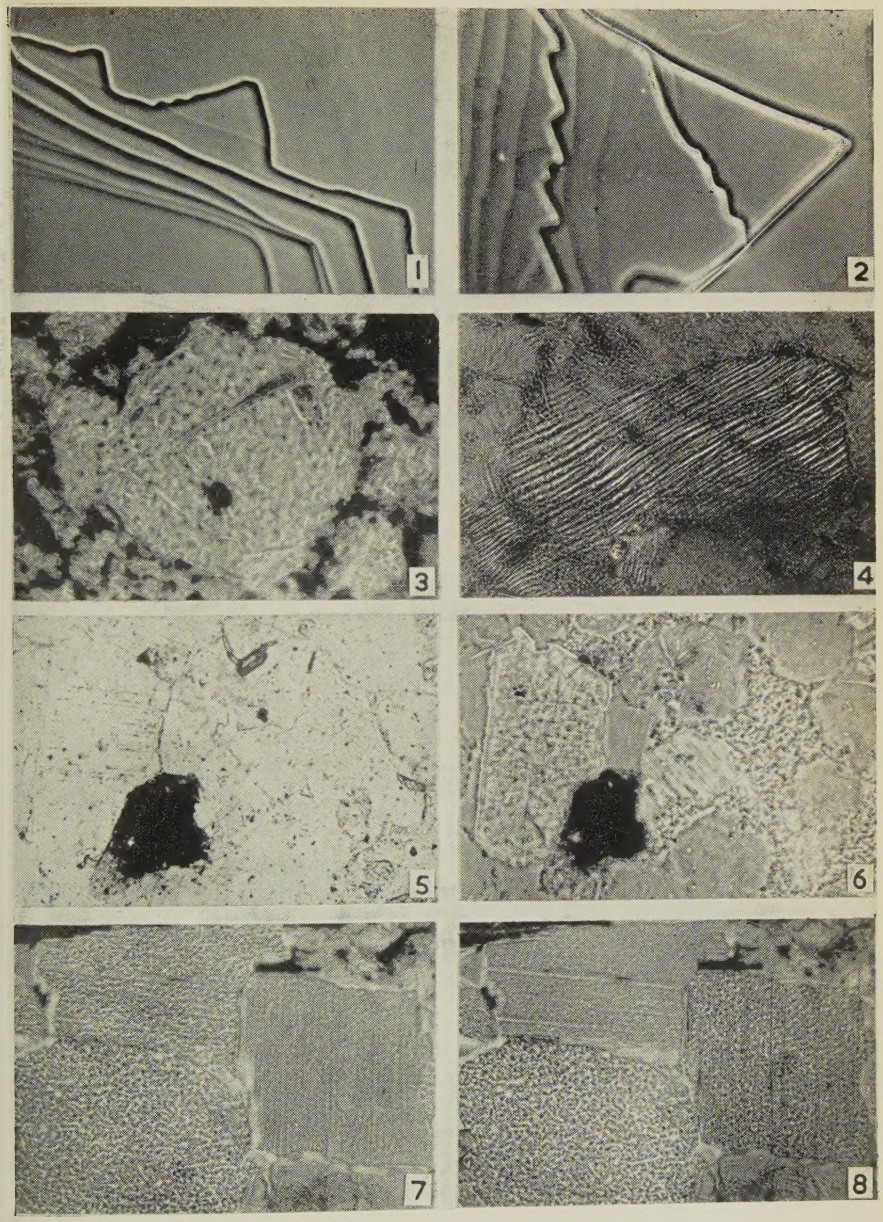
FIG. 17. Microcline-microperthite in Leinster granite. Ordinary illumination. ×60.

FIG. 18. Same field. 0A. ×60.

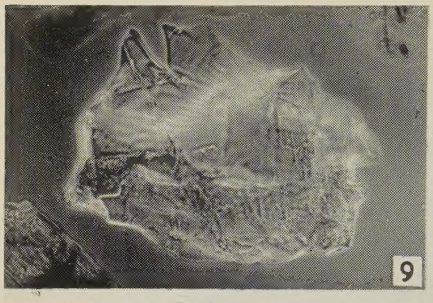
FIG. 19. Same field. ∞ B. ×60.

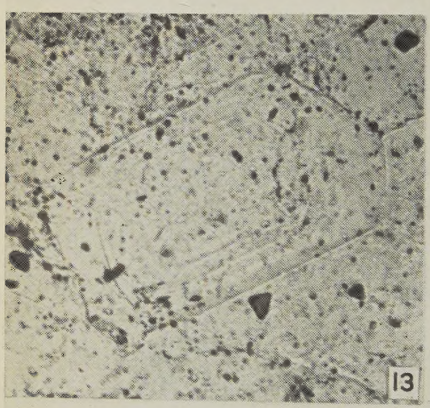
FIG. 20. Same field. Phase-contrast. ×60.

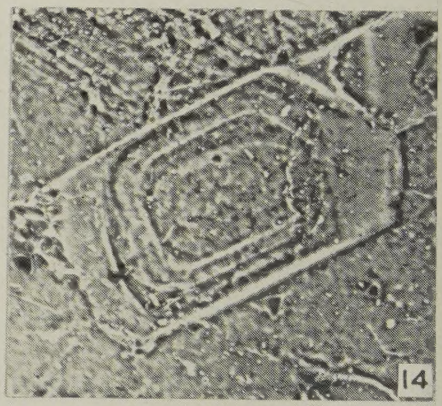
The cost of these three plates is met by the Miers Memorial Fund.

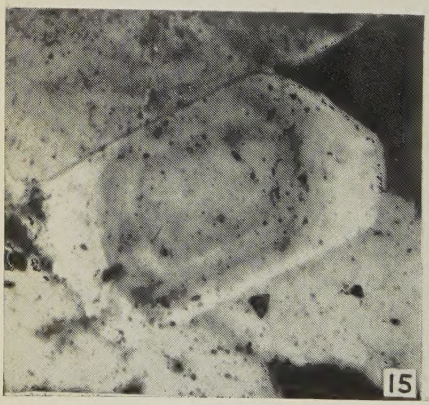


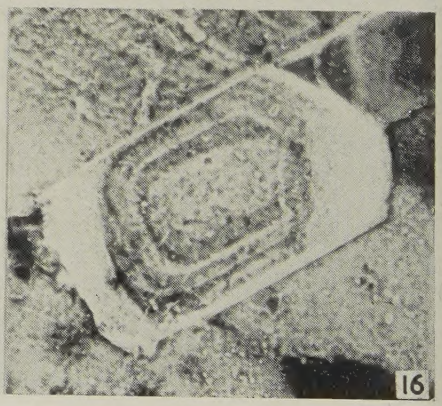
F. Smithson: Phase-contrast Microscopy



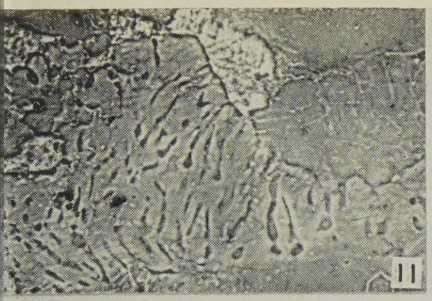


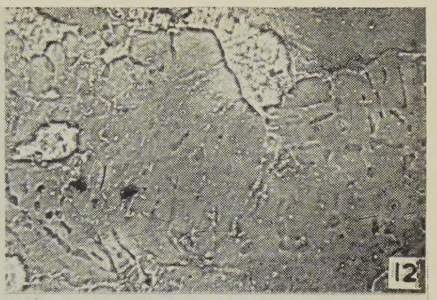


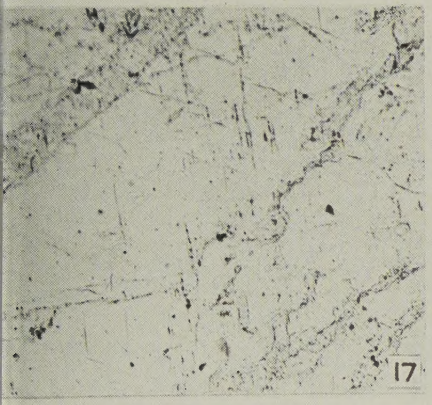


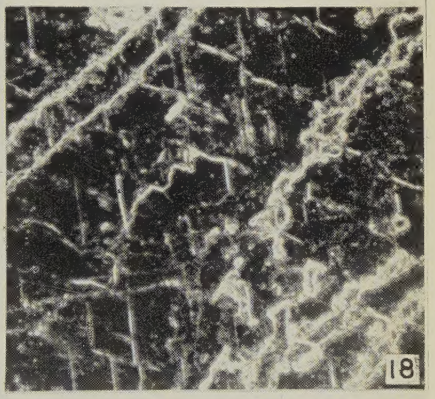


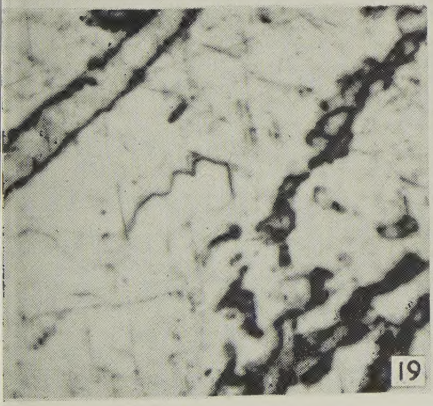
F. SMITHSON: PHASE-CONTRAST MICROSCOPY

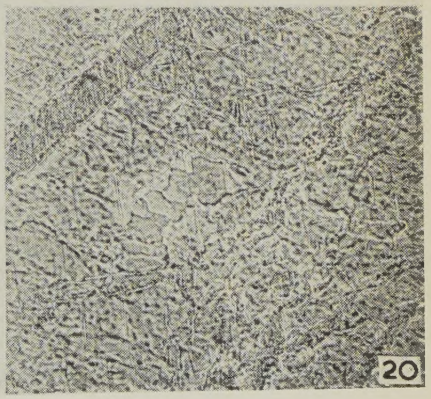












F. Smithson: Phase-contrast Microscopy